

Superfluid effects on gauging core temperatures of neutron stars in low-mass X-ray binaries

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ABSTRACT

Neutron stars accreting matter from low-mass binary companions are observed to undergo bursts of X-rays due to the thermonuclear explosion of material on the neutron star surface. We use recent results on superfluid and superconducting properties to show that the core temperature in these neutron stars may not be uniquely determined for a range of observed accretion rates. The degeneracy in inferred core temperatures could contribute to explaining the difference between neutron stars which have very short recurrence times between multiple bursts and those which have long recurrence times between bursts: short bursting sources have higher temperatures and normal neutrons in the stellar core, while long bursting sources have lower temperatures and superfluid neutrons. If correct, measurements of the lowest luminosity from among the short bursting sources and highest luminosity from among the long bursting sources can be used to constrain the critical temperature for the onset of neutron superfluidity.

Key words: accretion, accretion discs — dense matter — neutrinos — stars: neutron — X-rays: binaries — X-rays: bursts

1 INTRODUCTION

Neutron stars (NSs) are created in the collapse and subsequent supernova explosion of massive stars. NSs begin their lives very hot (with core temperatures $kT > 10$ MeV) but cool rapidly by the emission of neutrinos. Neutrino emission processes (and hence cooling of the NS) depend on uncertain physics at the extreme supra-nuclear densities of the NS core (see Tsuruta 1998; Yakovlev & Pethick 2004; Page et al. 2006, for review). Current theories indicate that the core may contain particles beyond what makes up normal matter, such as hyperons and deconfined quarks, and even the normal matter may be composed of a neutron superfluid and proton superconductor (Migdal 1959; see, e.g., Lattimer & Prakash 2004; Haensel et al. 2007, for review).

Superfluidity has two important effects on neutrino emission and NS cooling: (1) suppression of emission mechanisms, like modified Urca processes, that involve superfluid constituents and (2) enhanced emission due to Cooper pairing of nucleons when the temperature decreases just below a critical temperature (Yakovlev & Pethick 2004; Page et al. 2006). The measurement of rapid cooling of the (youngest in our Galaxy; Ho & Heinke 2009) NS in the Cassiopeia A supernova remnant (Heinke & Ho 2010; Shternin et al. 2011) provides the first direct evidence for the existence of superfluid components in the core of a NS and constrains the

critical temperatures for the onset of superfluidity of neutrons T_{cn} (in the triplet state) and protons T_{cp} (in the singlet state), i.e., $T_{\text{cn,max}} \approx (5-9) \times 10^8$ K and $T_{\text{cp}} \sim (2-3) \times 10^9$ K (Page et al. 2011; Shternin et al. 2011).

In contrast to the NS in Cassiopeia A, many old NSs are found in binary systems. These binaries are seen in X-rays, which are produced when material from the companion accretes onto the NS. If the companion has a low stellar mass, the systems are known as low-mass X-ray binaries (LMXBs). Many LMXBs undergo bright X-ray bursts due to unstable thermonuclear burning of hydrogen and/or helium in the surface layers of the NS (see, e.g., Lewin et al. 1993; Bildsten 1998; Strohmayer & Bildsten 2006; Galloway et al. 2008, for review). Bursts are sometimes observed to recur in individual sources, and recurrence times between multiple bursts span a wide range, from minutes to days (Galloway et al. 2008; Keek et al. 2010). However, recurrence times $\lesssim 1$ hr are too short for the NS to accrete enough fuel for subsequent bursts (Lewin et al. 1993; Woosley et al. 2004). Keek et al. (2010) studied the properties of these bursts and found fifteen LMXBs that underwent short recurrence time X-ray bursts. Only five of the NSs in these LMXBs have measured rotation rates ν_s , and all five possess $\nu_s \gtrsim 550$ Hz. This would suggest that fast spins play an important role in causing short recurrence times, e.g., through stellar r-mode oscillations (Ho et al. 2011). However, the recent discovery of IGR J17480–2446 (in the globular cluster Terzan 5), which is a slow-spinning ($\nu_s = 11$ Hz) LMXB

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(Bordas et al. 2010; Strohmayer & Markwardt 2010) that shows bursts with recurrence times as short as 3 min, suggests rotation may not be a crucial ingredient (Motta et al. 2011).

In light of the recent superfluid results from studies of the Cassiopeia A NS, we revisit the method used to infer core temperatures of NSs in LMXBs. We demonstrate that superfluid effects can lead to non-uniqueness in the inferred temperatures (if T_{cn} is low enough) and offer this high/low temperature degeneracy as a possible explanation for the difference between short/long recurrence time LMXBs. In Section 2, we briefly discuss the accretion-induced nuclear heating of a NS core. Section 3 describes the standard neutrino cooling mechanism, as well as our model of superfluid neutrino cooling. In Section 4, we determine the core temperature for NSs in LMXBs from a balance between heating and cooling and apply our results to short and long recurrence time LMXBs. We summarize in Section 5.

2 ACCRETION/NUCLEAR HEATING

Many NSs in LMXBs are seen to undergo long-term accretion; for each source, the measured average flux F and distance d provide an estimate of the accretion luminosity $L_{\text{acc}} = 4\pi d^2 F$. Accretion onto the NS surface releases a gravitational energy per nucleon $Q_{\text{grav}} = GMm_b/R = 190 \text{ MeV}(M/1.4 M_\odot)(R/10 \text{ km})^{-1}$, where M and R are the NS mass and radius, respectively, m_b is the nucleon mass, and M_\odot is the solar mass. Only a small fraction of this energy diffuses into and heats the core (Hanawa & Fujimoto 1984; Fujimoto et al. 1987). On the other hand, compression by accreted matter induces nuclear reactions in the deep crust, which release $Q_{\text{nuc}} \approx 1.5 \text{ MeV nucleon}^{-1}$ (Haensel & Zdunik 1990, 2008), and this heats the core directly by a luminosity (Brown et al. 1998; Brown 2000)

$$L_{\text{heat}} = (Q_{\text{nuc}}/Q_{\text{grav}})L_{\text{acc}} = 0.0078 L_{\text{acc}}. \quad (1)$$

We note that r-mode heating yields $L_{\text{heat}} = 0.046(\nu_s/300 \text{ Hz})L_{\text{acc}}$ and is a more efficient heat source for fast-spinning NSs (Brown & Ushomirsky 2000; Ho et al. 2011).

3 NEUTRINO COOLING

At high internal temperatures, neutron stars cool by neutrino emission (see Tsuruta 1998; Yakovlev & Pethick 2004; Page et al. 2006, for review); cooling via neutrino emission dominates over photon emission at our considered temperatures ($T \gtrsim 10^8 \text{ K}$). The neutrino luminosity L_ν depends on the NS equation of state (EOS) since L_ν is calculated by integrating the density-dependent emissivity over the volume of the star. Standard (slow) cooling is primarily determined by the modified Urca processes. For simplicity, we use the general result from Shapiro & Teukolsky (1983)

$$L_\nu^{\text{MU}} \approx 7.4 \times 10^{31} \text{ ergs s}^{-1} (T/10^8 \text{ K})^8, \quad (2)$$

where we assume $M = 1.4 M_\odot$ and constant $\rho = \rho_{\text{nuc}}$ just for the above equation.

The modified Urca neutrino luminosity L_ν^{MU} given by eq. (2) assumes normal nucleons in the stellar core. When nucleons are superfluid, the modified Urca processes involving these nucleons are suppressed. In addition, a new neutrino emission channel, due to Cooper pair formation and

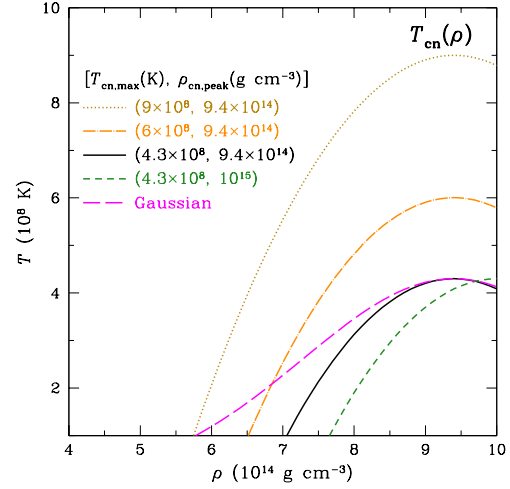


Figure 1. Simple models of the neutron superfluid critical temperature $T_{\text{cn}}(\rho)$ (see text for details). See Fig. 3 for the resulting neutrino luminosities using these models.

breaking, opens up and is important near the critical temperature for the onset of superfluidity (T_{cp} for protons and T_{cn} for neutrons; see, e.g., Yakovlev et al. 1999a, and references therein). We use Yakovlev et al. (1999b); Page et al. (2004, 2009) to calculate the neutrino emissivities due to modified Urca processes, accounting for superfluid suppression, and Cooper pair formation processes. We take a constant $T_{\text{cp}} = 3 \times 10^9 \text{ K}$, so that neutrino emission from Cooper pairing of protons is negligible, and the only effect of superconducting protons is suppression of modified Urca processes. For $T_{\text{cn}}(\rho)$, we use simplified models that depend on three parameters: the maximum critical temperature $T_{\text{cn,max}}$, the density at which this peak occurs $\rho_{\text{cn,peak}}$, and the width of the peak. For example, we consider a model that approximates model (a) of Shternin et al. (2011), i.e.,

$$T_{\text{cn}}(\rho) = T_{\text{cn,max}} - 6 \times 10^7 \text{ K} \left(\frac{\rho - \rho_{\text{cn,peak}}}{10^{14} \text{ g cm}^{-3}} \right)^2. \quad (3)$$

Figure 1 shows $T_{\text{cn}}(\rho)$ for $T_{\text{cn,max}} = 4.3 \times 10^8 \text{ K}$ and $\rho_{\text{cn,peak}} = 9.4 \times 10^{14} \text{ g cm}^{-3}$. Also shown is $T_{\text{cn}}(\rho)$ for several other values of $T_{\text{cn,max}}$ and $\rho_{\text{cn,peak}}$. The impact of the width of $T_{\text{cn}}(\rho)$ is examined by comparing the quadratic density-dependence of eq. (3) with a $T_{\text{cn}}(\rho)$ that is given by a Gaussian profile

$$T_{\text{cn}}(\rho) = T_{\text{cn,max}} \exp \left[- \left(\frac{\rho - \rho_{\text{cn,peak}}}{3 \times 10^{14} \text{ g cm}^{-3}} \right)^2 \right]; \quad (4)$$

this is shown in Fig. 1 for $T_{\text{cn,max}} = 4.3 \times 10^8 \text{ K}$ and $\rho_{\text{cn,peak}} = 9.4 \times 10^{14} \text{ g cm}^{-3}$. These phenomenological models for $T_{\text{cn}}(\rho)$ are approximations of more detailed but uncertain theoretical models (see, e.g., Lombardo & Schulze 2001; Page et al. 2004, 2009, and references therein; see also Kaminker et al. 2002; Gusakov et al. 2004).

The superfluid neutrino luminosity L_ν^{SF} is obtained by integrating the neutrino emissivities over the volume of the star and accounting for $T_{\text{cn}}(\rho)$. We use a stellar model based on the Akmal-Pandharipande-Ravenhall EOS (Akmal et al. 1998; Heiselberg & Hjorth-Jensen 1999; Gusakov et al. 2005) with $M = 1.4 M_\odot$ and $R = 12 \text{ km}$. For

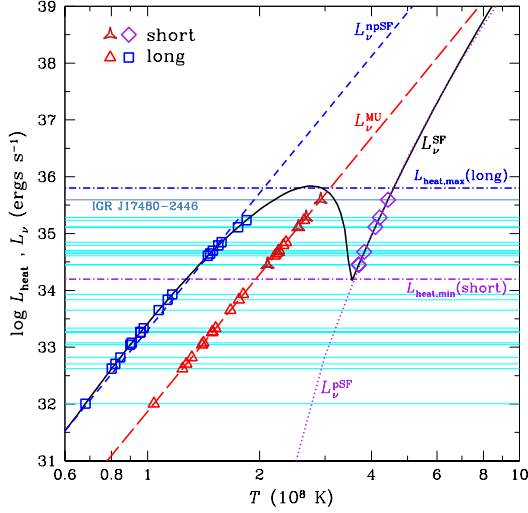


Figure 2. Heat generated by accretion and nuclear reactions L_{heat} compared to the neutrino cooling luminosity L_{ν} as a function of neutron star core temperature T . The upper (lower) dot-dashed line is the highest (lowest) observed L_{heat} from among all long (short) recurrence time bursts, while the solid horizontal lines are L_{heat} for fast-spinning LMXBs and IGR J17480–2446. The long-dashed line is the modified Urca luminosity L_{ν}^{MU} . Triangles and starred-triangles indicate the intersection of L_{heat} and L_{ν}^{MU} , which determines T for each long and short recurrence time LMXB, respectively. The thick solid line is L_{ν}^{SF} with $T_{\text{cn,max}} = 4.3 \times 10^8$ K and $\rho_{\text{cn,peak}} = 9.4 \times 10^{14}$ g cm $^{-3}$, and squares and diamonds are where $L_{\text{heat}} = L_{\nu}^{\text{SF}}$ for each long and short LMXB, respectively. The short-dashed and dotted lines are approximate fits to L_{ν}^{SF} in the strongly-superfluid and non-superfluid neutron regimes, respectively.

simplicity, we have not taken into account other (less important) neutrino emission processes in the core and crust, nor have we examined the effect of the EOS, which determines the onset of more efficient (fast) neutrino emission processes (such as direct Urca or those associated with hyperon or quark condensates) and partly determines the fraction of the NS that is superfluid; these issues are beyond the scope of this work.

4 NEUTRON STAR CORE TEMPERATURES

Figure 2 shows the heating rate L_{heat} [eq. (1)] and neutrino luminosities L_{ν} [= L_{ν}^{MU} from eq. (2) and L_{ν}^{SF} for $T_{\text{cn,max}} = 4.3 \times 10^8$ K and $\rho_{\text{cn,peak}} = 9.4 \times 10^{14}$ g cm $^{-3}$]. The horizontal, solid lines indicate L_{heat} for LMXBs with $\nu_s \gtrsim 100$ Hz, as well as IGR J17480–2446 with $\nu_s = 11$ Hz, using fluxes and distances from Watts et al. (2008); Ferrigno et al. (2011); Motta et al. (2011). Also plotted are L_{heat} calculated from the highest luminosity ($\approx 8 \times 10^{37}$ ergs s $^{-1}$) seen amongst all long recurrence time LMXBs and the lowest luminosity ($\approx 2 \times 10^{36}$ ergs s $^{-1}$) seen amongst all short recurrence time LMXBs (Keek et al. 2010); hereafter we follow Keek et al. (2010) in defining “long” LMXBs as those that undergo multiple bursts with recurrence times ≥ 1 hr and “short” LMXBs as those with recurrence times ≤ 1 hr. The various symbols denote $L_{\text{heat}} = L_{\nu}(T)$. Figure 3 compares L_{ν}^{SF} for the different $T_{\text{cn}}(\rho)$ profiles shown in Fig. 1.

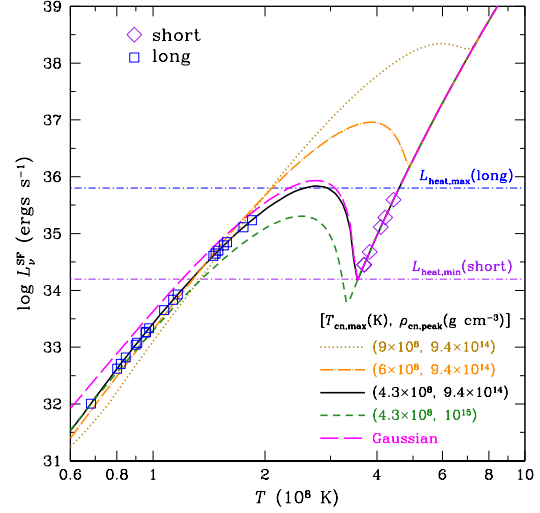


Figure 3. Neutrino luminosity L_{ν}^{SF} as a function of neutron star core temperature T , where the different curves are L_{ν}^{SF} calculated using models of the neutron superfluid critical temperature $T_{\text{cn}}(\rho)$ shown in Fig. 1. The upper (lower) horizontal dot-dashed line is the highest (lowest) observed L_{heat} from among all long (short) recurrence time bursts. Squares and diamonds are where $L_{\text{heat}} = L_{\nu}^{\text{SF}}$ (4.3×10^8 K, 9.4×10^{14} g cm $^{-3}$) for each fast-spinning LMXB with long and short recurrence times, respectively.

The intersection of the curves L_{heat} and L_{ν} yields the core temperature of each NS. In the case of NSs cooling purely by modified Urca processes (unsuppressed by nucleon superfluidity), the core temperature obtained from setting $L_{\text{heat}} = L_{\nu}^{\text{MU}}$ is given by

$$T^{\text{MU}} = 1.3 \times 10^8 \text{ K} \left(L_{\text{acc}} / 10^{35} \text{ ergs s}^{-1} \right)^{1/8}. \quad (5)$$

It is evident that, assuming the NS core is heated by accretion and cools by modified Urca processes, there is no clear distinction between NSs which have short and long recurrence times: Fig. 2 shows the T of several long sources interspersed between the T of short sources.

When superfluid effects are taken into account, there are pronounced differences. At $T \gtrsim T_{\text{cn,max}}$ (and $T \ll T_{\text{cp}}$), neutrons are normal while protons are superconducting. The latter suppresses modified Urca processes, so that $L_{\nu}^{\text{SF}} (< L_{\nu}^{\text{MU}})$ is approximately given by (see Fig. 2)

$$L_{\nu}^{\text{pSF}} \approx 4 \times 10^{39} \text{ ergs s}^{-1} [\log(T/10^8 \text{ K})]^{21}. \quad (6)$$

Setting $L_{\nu}^{\text{pSF}} = L_{\text{heat}}$, the core temperature is then

$$\log T^{\text{pSF}} = 8 + 0.5 \left(L_{\text{acc}} / 10^{35} \text{ ergs s}^{-1} \right)^{1/21}. \quad (7)$$

Since cooling is less efficient in this case, the inferred core temperatures are higher than those obtained from eq. (5). At $T < T_{\text{cn,max}}$, neutrino emission is enhanced due to the formation of neutron Cooper pairs; this new emission channel dominates the modified Urca emission. Cooling is more efficient and can result in a lower inferred T . When neutrons (and protons) are strongly superfluid ($T \ll T_{\text{cn,max}}$), Gusakov et al. (2004) find that the neutrino luminosity from Cooper pair formation has the same T^8 -dependence as the modified Urca processes but with a much higher efficiency [i.e., larger coefficient in eq. (2)]. We find L_{ν}^{SF} can be fit by (see Fig. 2)

$$L_{\nu}^{\text{npSF}} \sim (20 - 30)L_{\nu}^{\text{MU}}; \quad (8)$$

from $L_{\nu}^{\text{npSF}} = L_{\text{heat}}$, we obtain

$$T^{\text{npSF}} = 9 \times 10^7 \text{ K } (L_{\text{acc}}/10^{35} \text{ ergs s}^{-1})^{1/8}. \quad (9)$$

The core temperature of NSs in relatively high-luminosity LMXBs may not be uniquely determined. If $T_{\text{cn,max}} \lesssim 8 \times 10^8 \text{ K}$ (see Figs. 2 and 3), there are two thermally stable (see below) values of the core temperature associated with a single observed accretion luminosity, for a range of $L_{\nu}^{\text{SF}} = L_{\text{heat}}$. For example, there is a factor of < 3 difference in the inferred T if $L_{\text{acc}} \sim (0.2 - 9) \times 10^{37} \text{ ergs s}^{-1}$ and $T_{\text{cn,max}} = 4.3 \times 10^8 \text{ K}$. The persistent luminosities of all LMXBs that show short recurrence time bursts lie within this range (Keek et al. 2010). To highlight this point, we place the six short LMXBs with measured spin periods (L_{acc} of the LMXB Aql X-1 and EXO 0748–676 are very similar and thus their inferred T are not noticeably different) on the high-temperature L_{ν}^{pSF} -branch and the seven long LMXBs on the low-temperature L_{ν}^{npSF} -branch. Note that there can be three values of T that cross each horizontal L_{heat} ; however the intermediate temperature is thermally unstable since a decrease in temperature leads to an increase in neutrino luminosity and hence causes even more rapid cooling.

At present, it is not known what causes LMXBs to undergo short versus long recurrence time bursts. Possibilities include variations in fraction of fuel burnt, mass accretion rate, or composition of accreted matter. As we have shown above, if $T_{\text{cn,max}} \sim (4 - 5) \times 10^8 \text{ K}$ [note the rapid cooling of the Cassiopeia A NS indicates $T_{\text{cn,max}} \approx (5 - 9) \times 10^8 \text{ K}$; Page et al. 2011; Shternin et al. 2011], another possibility is that short LMXBs have intrinsically hotter core temperatures than long LMXBs. This would indicate that neutrons are normal in the core of short recurrence time LMXBs (so that L_{ν}^{SF} is given by L_{ν}^{pSF}), while core neutrons are superfluid in the long recurrence time LMXBs (so that $L_{\nu}^{\text{SF}} \sim L_{\nu}^{\text{npSF}}$).

A core temperature that is a factor of three hotter produces a surface temperature that is $\sim 3^{1/2}$ hotter (Gudmundsson et al. 1982) and a surface flux that is $\sim (3^{1/2})^4$ brighter. The higher surface temperature and flux may be sufficient to alter the temperature in the nuclear burning layers and shorten the time intervals between ignition of unstable burning. For matter accreting at a rate \dot{M} , the time to replenish the nuclear fuel (i.e., burst recurrence time) is $\sim R^2 y_{\text{ign}} / \dot{M} \propto T^{-5/2}$, where y_{ign} is the ignition depth/column (Bildsten 1998; see also Cumming & Bildsten 2000). Thus a factor of three higher core temperature could shorten the recurrence time by at least that amount. As discussed in Sec. 1, previous works calculate burst recurrence times that are longer than observed, but numerical simulations currently being performed suggest shorter times may be possible (Keek & Heger, in preparation).

A consequence of (possibly) higher core temperatures in short LMXBs is that one might expect the quiescent luminosity L_{q} (i.e., when the NS is not accreting significantly) of short LMXBs to be higher than that of (cooler) long LMXBs. Previous works (see, e.g., Colpi et al. 2001; Yakovlev et al. 2004; see however Levenfish & Haensel 2007) studying quiescent emission do not account for superfluidity in the appropriate regime and thus do not see the effects described here. Figure 4 shows L_{q} for LMXBs

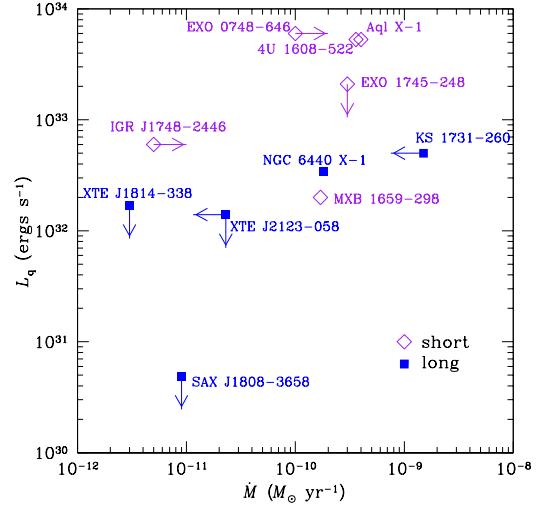


Figure 4. Quiescent luminosity L_{q} as a function of time-averaged mass accretion rate \dot{M} of LMXBs that are seen to produce multiple nuclear X-ray bursts. Diamonds and squares are for short and long recurrence time LMXBs, respectively, and arrows indicate upper or lower limits.

with measured nuclear X-ray bursts (Heinke et al. 2007, 2009; Galloway et al. 2008; Degenaar & Wijnands 2011; Degenaar et al. 2011; Díaz Trigo et al. 2011). Note that surface burning effects can dominate core temperature variations at instantaneous $\dot{M} \gtrsim 6 \times 10^{-9} M_{\odot} \text{ yr}^{-1}$. Note also that Levenfish & Haensel (2007) studied predictions for L_{q} and \dot{M} and found that neutron superfluidity can create a dichotomy amongst LMXBs. Though there are many uncertainties involved, especially in distance and accretion rates, the observations suggest that short recurrence time LMXBs may be intrinsically hotter.

Finally, if short recurrence time LMXBs do indeed possess hotter core temperatures, then measurements of the minimum and maximum accretion luminosities of bursts from short LMXBs and long LMXBs, respectively, can be used to constrain the neutron superfluid critical temperature $T_{\text{cn}}(\rho)$. This is illustrated in Fig. 3, where it is clear that the accretion luminosities for LMXBs can constrain $T_{\text{cn,max}}$ and $\rho_{\text{cn,peak}}$, while the width of $T_{\text{cn}}(\rho)$ is not as important in determining the qualitative behavior of L_{ν}^{SF} .

5 DISCUSSION

We used the accretion luminosity measured from observations of LMXBs to determine the heating rate of the NSs in these systems. By balancing heating with cooling (via neutrino emission), we determined NS core temperatures. Uncertainties in the accretion/heating efficiency and nuclear energy release have a small effect on the inferred temperatures because of the strong temperature scalings in the neutrino emissivities. We found that neutrino emission from Cooper pairing neutrons can yield a non-unique determination of the core temperature. We explored one possible implication, i.e., the observed variation in recurrence times between multiple nuclear X-ray bursts could be a manifestation of differences (by a factor of $\lesssim 3$) in NS core temperature. LMXBs that undergo nuclear-powered bursts with long recurrence times have lower core temperatures and neutrons

that are superfluid, while those with short recurrence time bursts have higher core temperatures and normal neutrons. Thus LMXBs which experience multiple bursts could provide constraints on properties of neutron superfluidity. We note that we have not examined the effect of higher temperatures on different burning regimes and implications for, e.g., long bursts and superbursts (see, e.g., Cumming et al. 2006; Strohmayer & Bildsten 2006, and references therein).

Previous studies find that sequences of short recurrence bursts involves, at most, a quadrupole set of bursts (Keek et al. 2010). However, the recently discovered source, IGR J17480–2446, shows tens of bursts in a single event (Motta et al. 2011). This could be the result of IGR J17480–2446 being the hottest of the known LMXBs (see Fig. 2). Note though that the short recurrence time bursts from IGR J17480–2446 may be different in nature than those seen in other sources (L. Keek, private comm.).

A natural question is what determines the state of the neutrons, or alternatively, which neutrino luminosity branch (see Figs. 2 or 3) does a particular LMXB lie on. Presumably a young NS or one that sustains long-term heating of its core above the peak in L_{ν}^{SF} will be on the higher T (or L_{ν}^{pSF}) branch. If subsequent accretion initiates multiple bursts, these bursts will recur on short timescales ($\lesssim 1$ hr). If accretion does not significantly heat the core, then the NS will move rapidly through the thermally unstable branch (where the neutrino luminosity increases as the temperature decreases) and shift to the lower T (or $\sim L_{\nu}^{\text{pSF}}$) branch; bursts from these NSs will recur with long timescales. On the other hand, if the maximum critical temperature for neutron (triplet) superfluidity $T_{\text{cn,max}} \gtrsim 6 \times 10^8$ K, then all LMXBs have core temperatures given by T^{npSF} [see eq. (9)].

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